1.0

2.8 | 2.5
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3.5 | 2.2

2.0

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1.8

1.25 | 1.4 | 1.6

MICROCOPY RESOLUTION TEST CHART

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Snowfall Rates Obtained From Radar Reflectivity Within a 50 km Range
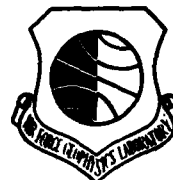
ROLAND J. BOUCHER

15 September 1981

METEOROLOGY DIVISION   PROJECT 6670
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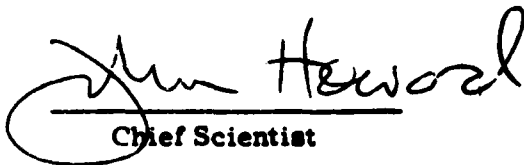
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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The snowy winter of 1978 in Massachusetts allowed five opportunities to test the dependability of a CPS-9, 3.2-cm radar to determine snowfall rate and total snowfall accumulation at up to seven measuring sites within 50 km of the radar.

Spaced at intervals of 0.5- to 1-h, 166 snowfall-rate measurements yielded a correlation coefficient of 0.88. However, in correlating the total storm snowfall, the amount of radar-measured snowfall above a reference —

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20. Abstract (Continued)

snowfall measurement site was made equal to the snowfall actually measured at this location. This calibration technique improved the storm snowfall correlation coefficient to 0.96.

2

Preface

The success of this project would not have been possible without the diligent
and accurate measurements of snowfall rates by five volunteer observers:
H.A. Brown, Chelmsford; J.H. Conover, Dedham, R.F. Lautzenheiser, Reading;
H.S. Muench, Hanscom AFB and Lexington; F.R. Skilling, Hingham; and by the
author, Natick. C.L. Bjerkaas processed the Doppler reflectivity and conferred
with and assisted the author in the interpretation of reflectivity data. P.J. Petrocchi
operated the CPS-9, 3.2 cm radar. G.M. Armstrong, A.W. Bishop, and W.A.
Smith operated the Doppler 5.4 cm radar. I.I. Gringorten reviewed the statistical
results. R.J. Donaldson Jr. reviewed and advised on the text and K.M. Glover
reviewed the project.

3/4

Contents

5

Illustrations

Tables

6

Snowfall Rates Obtained From Radar
Reflectivity Within a 50 km Range

1. INTRODUCTION

Radar has been used, very successfully, in measuring rainfall over watersheds
to determine runoff for hydrologists and river forecasters. Results are far super-
ior to techniques relying solely on a scattering of rain gauges. Carlson and Marshall
(1968),[1] Jatila (1973),[2] Wilson (1975),[3] and Collier and Larke (1978)[4] have examined
the utility of radar reflectivity in determining snow accumulation for a total storm
or a season. An alternative approach, one considered initially in this report, is
the systematic and accurate use of radar reflectivity during a snowstorm to yield
estimates of current snowfall rates over target points within a 50 km range. Ulti-
mately, this approach may lead to a technique for improving snow forecasts, at
short time intervals of 1 or 2 h.

1. Carlson, P.E., and Marshall, J.S. (1972) Measurements of snowfall by radar,
   J. Appl. Meteor. 11:494-500.

2. Jatila, E. (1973) Experimental study of the measurement of snowfall by radar,
   Univ. of Helsinki, Dept. of Met. Paper No. 122, Geophysica 12(No.2):1-10.

3. Wilson, J.W. (1975) Measurement of Snowfall by Radar During the IFYGL,
   Preprints, 16th Radar Meteor. Conf., Amer. Meteor. Soc., Boston,
   Massachusetts, 508-513.

4. Collier, C.G., and Larke, P.R. (1978) A case study of the measurement of
   snowfall by radar: An assessment of accuracy, Quart. J.R. Met. Soc.
   104:615-621.

The objectives of this project are first, to examine the reliability of determining current storm snowfall rate solely on the basis of accurate radar reflectivity measurements and second, to examine the reliability of the total storm average snowfall rate as determined from radar reflectivity.

A trial number of correlations of radar reflectivity and snowfall rates, first done during March 1976 and later during the months of December 1976 and January 1977 (Boucher, 1978[5]), supplied good evidence of an excellent relationship between these two variables and the potential value of reflectivity as an indicator of the snowfall rate. These early favorable results encouraged a continuation of radar-snowfall observations during the very snowy New England winter of 1977-78 and led to persistent radar and snowfall observations during five snowstorms. From a statistical analysis of 166 pairs of reflectivity and snowfall rate observations made during the storms in the winter of 1977-78, the overall correlation coefficient of these variables was $r = 0.878$ (Boucher, 1980[6]). However, when the snowfall-reflectivity relationship was calibrated by referenced snowfall measurement, the total storm correlation coefficient increased to $r = 0.96$.

2. GENERAL DISCUSSION

2.1 Radar Observations

The radar reflectivity in dBZ, where $dBZ = 10 \log Z$, was obtained from the CPS-9, 3.2 cm wavelength radar of 1° beamwidth, for the correlation of five 1978 snowstorms analyzed. In addition, one storm, 20 January, was also observed with the porcupine Doppler radar that has a wavelength of 5.4 cm, a 0.89° beamwidth in the azimuth, and a 1.0° beamwidth in the vertical. The results for the Doppler radar will be discussed in Section 3, Storm Analysis.

Frequent checks on the calibration of the radar signal are required in order to perform accurate reflectivity measurements during a snowstorm. There are, however, natural reasons for deviations occurring in the correlation between snowfall rate and radar reflectivity. These are difficult to cope with, particularly when using radar reflectivity based solely on radar calibration to determine snowfall rate during a snowstorm. Such deviations stem from changes in the snow particle size distributions, alterations in snow crystal structure, and in particular, from resulting variations in the fall speed of the snow.

5. Boucher, R.J. (1978) Correlation of Radar Reflectivity and Snowfall Rate During Moderate to Heavy Snow, Preprints, 18th Conf. on Radar Meteorology, Amer. Meteor. Soc., Boston, Massachusetts, 328-331. AFGL-TR-78-0079, AD A053 186.

6. Boucher, R.J. (1980) Snowfall Rate Determined from Radar Reflectivity, Preprints, 19th Conf. on Radar Meteorology, Amer. Meteor. Soc., Boston, Massachusetts, 438-439, AFGL-TR-80-0131, AD A084 297.

Ohtake and Henmi (1970)[7] indicate large differences in fall speeds between dendrites (approximately 50 to 100 cm sec^{-1}) and, at the other extreme, graupel and ice pellets ranging upward to near the fall speed of equivalent mass rain drops. Nakaya's (1954)[8] earlier measurements give mean fall velocities of 30 to 60 cm sec^{-1} for dendrites, 100 cm sec^{-1} for rimed crystals, and 180 cm sec^{-1} for graupel. While these values may differ somewhat from the Ohtake-Henmi values, they still show how the variations in snow crystal particle types do alter the fall speeds, which, in turn, affect the reflectivity.

There is still another, occasionally significant, problem arising from an effect referred to in radar meteorology as the "bright band". This phenomenon, associated with the snow melting layer, may, at times, lead to an appreciable increase in reflectivity indicating a greater snowfall rate than measured. The occurrence of the "bright band" may vary considerably during a storm, adding to difficulties in interpreting radar measurements. Consequently, it is desirable to monitor hourly reports to detect the occurrence of wet snow, ice pellets, graupel, snow changing to rain, or other evidence of possible "bright band" contamination.

Many investigators have determined that reflectivity (Z) is related to precipitation (R) by $Z = aR^b$, where the coefficients a and b vary with either raindrop size distribution or with size, shape, and structure of snow crystals or snowflakes. All of the analyzed storms, with the exception of 20 January 1978, showed good agreement in their snowfall rate — radar reflectivity correlation.

The CPS-9 radar reflectivity data were displayed in a PPI format, observed at 0° antenna elevation and over a range of 120 km. These data were processed in four colors by the Weather Radar Processor and Display (Petrocchi, 1976[9]), each color representing a range of reflectivity values. Reflectivity displays were recorded on a disc every 6 min. The recorded presentation color ranges may be, and were in some cases, readjusted to present the best coverage of the reflectivity values. Working with transparencies of the 3.5 cm PPI disc displays, the reflectivity values over the snow observation points were recorded in such a way as to distinguish between the borders and midpoints of the color areas. An attempt was made to interpolate the derived reflectivity values and arrive at a more accurate estimate.

7. Ohtake, T., and Henmi, T. (1970) Radar Reflectivity of Aggregated Snowflakes. Preprints, 14th Radar Meteor. Conf., Amer. Met. Soc., Boston, Massachusetts, 209-210.

8. Nakaya, U. (1954) Snow Crystals Natural and Artificial, Harvard Univ. Press, Cambridge, Massachusetts.

9. Petrocchi, P.J. (1976) Operational Capability of a Weather Radar Time Lapse Color Display System, Preprints, 17th Radar Meteor. Conf., Amer. Meteor. Soc., Boston, Massachusetts, 562-565. AFGL-TR-76-0257, AD A032 005.

For all but one storm, 20 January 1978, radar observations were limited to the 3.2 cm radar. On 20 January, the 5.4 cm radar, operating at 0.7° elevation angle, provided a color display with 16 contours of reflectivity. The 5.4 cm radar reflectivity was digitized on a scale of dBZ ranging from 10 to 41 dBZ in single units. Five values, one over the snow measuring station, four others immediately north, south, east, and west covering an area of 3.2 km^2, were averaged.

2.2 Snowfall Rate Measurement

A most important procedure in this project was the accurate observation of snowiall or snow increment rate at the ground level. This was performed at up to eight different locations within a 50 km range to the east, southeast, and south of the radar site. Locations of these with respect to the radar are shown in Figure 1.
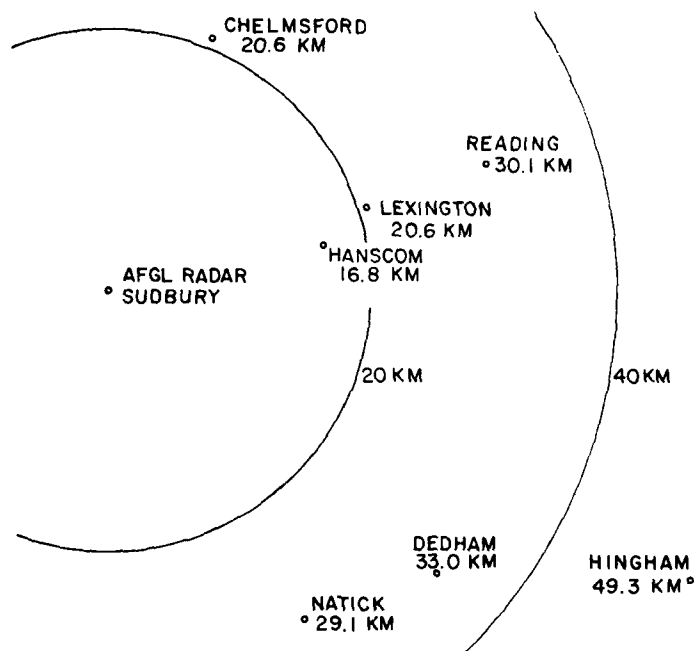

Figure 1. Location of Snowfall Rate Measuring Stations Within 50 km of the Radar Site

Depending principally on the intensity of the snowfall rate, measurements were made either hourly or half-hourly. Since most New England snowstorms are accompanied by wind, a great deal of care was taken to avoid the effect of drifting

10

adversely affecting the snowfall rate measurements. The first step was to use about a 2-ft square firm measuring surface, such as masonite, kept flush with the snow surface level and cleaned off and replaced after each snow accumulation measurement. The purpose of this procedure was to establish a level measuring surface in order to eliminate, to the extent possible, the blowing off of snow from higher level snow surfaces or the filling in of low spots by wind drift action. One additional safeguard was the selection of two snow measuring sites. This permitted the use of the snow data from one area that has the lesser amount of drifting, but also doubled the time required for measuring.

Snow accumulations were measured by observers in tenths of an inch. Hourly temperatures were recorded and notes were kept of the general type of snow crystal, the presence of ice pellets, the occurrence of rain, intensity of snow, visibility, wind direction, and estimated or measured wind velocity.

The purpose of the care recommended in the measurement of snow accumulation is to obtain as accurate a measurement of the snowfall rate as possible for correlation with radar reflectivity. Snowfall and radar reflectivity measurements are made at the same geographical point. No effort has been taken to allow for wind advection of the falling snow down to the ground measuring point. If this could be done realistically there might be an improved correlation between snowfall rate and reflectivity. However, since the direction and speed of snow advection would be linked to the wind direction and speed differences at certain critical levels and, further, since these wind elements vary appreciably from one storm to another and even within the same storm, concern about wind effect would introduce another variable and further complicate the data reduction process.

2.3 Correlation of Reflectivity and Rate of Snowfall

The two variables correlated were reflectivity, dBZ (dBZ = $10 \log Z$), as measured by radar, and the snowfall rate, $\log S$, as determined by ground observers. The CPS-9 PPI reflectivity display of the $0°$ elevation angle radar observation photographed on 35 mm transparencies was the basic form of the radar data. These transparencies were routinely projected onto a base map, similar to Figure 1, containing the radar site and seven other snow measuring points. From these projected radar observations, reflectivity values (dBZ) were determined for each snow measuring point active during the storm. The reflectivity values, from each 6-min radar observation, were then averaged for the snowfall rate measuring period, ranging from 1/2 to 1 h. Since the radar reflectivity over a snow measuring point in the $1°$ width of the radar beam was an aggregation of the reflectivity through the beam, a sufficient time was needed for the snow, as seen by the radar, to reach the snow measuring point. In order to account for this delay, the reflectivity measurements were correlated with the snowfall rates at five time lags

11

ranging from 0 to 30 min between the average reflectivity values and the snowfall rates. The correlation coefficients (r) for all data for the five 1978 snowstorms are listed, by lags, in Table 1.

Table 1. Correlation Coefficients at Five Lags for Five Storms in 1978

Time Lag, Snowfall Measurement Minus Reflectivity Measurement	Correlation Coefficients	No. of Points
Zero	0.839	165
10 min	0.871	166
15	0.878	166
20	0.872	166
30	0.843	165

The highest r value is for the 15-min lag, r = 0.878, but the range is small since for no lag, r = 0.839 and for a 30-min lag, r = 0.843. The 15-min lag data are plotted on the correlation diagram, as shown in Figure 2. While the locus of the line of regression of log S (snowfall rate) on dBZ (radar reflectivity), $S = 0.0203 \, Z^{0.563}$ gives the most probable value of snowfall rate within 50 km of the radar on the basis of the radar reflectivity measurement, the standard error of estimate (SEE), or the measure of the scatter about the line of regression, is indicated by the two dashed lines parallel to the regression line in Figure 2. When the values are approximately normally distributed about the line of regression, one SEE includes 68 percent of the points about the line. In this case the SEE actually encompasses 73.5 percent of the snowfall rates. Table 2 tabulates the line of regression values of radar reflectivity corresponding to hourly snowfall rates ranging from 0.1 in. h^{-1} to 3.0 in. h^{-1} (2.54 mm h^{-1} to 76.2 mm h^{-1}) and the SEE or scatter in snowfall rate values. It will be noted that in keeping with the use of logarithmic values for snowfall rates the amount of scatter increases with the increase in snowfall rate.

12
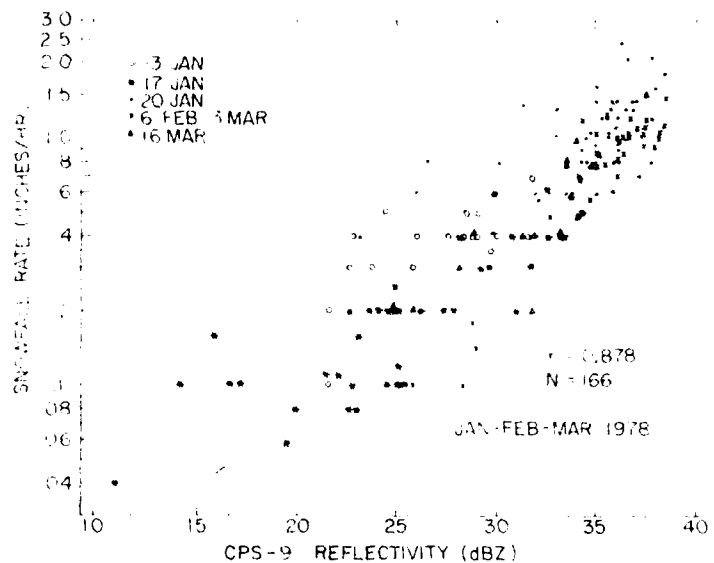
Figure 2. Correlation of Radar Reflectivity and Snowfall
Rate Within 50 km of the Radar During January, February,
and March 1978. Solid line is the regression line; two-
dashed lines the standard error of estimate

Table 2. A Tabulation of Snowfall Rate in Inches (in.) and Millimeters (mm) Per
Hour and CPS-9 Radar Reflectivity and the Standard Error of Estimate Range of
Snowfall Rate

Reflectivity (dBZ)	Snowfall Rate		Standard Error of Estimate (-33% to +51% of regression value)			
	(in. h^{-1})	(mm h^{-1})	(in. h^{-1})		(mm h^{-1})	
19.5	0.1	2.54	0.07 to 0.15		0.178 to	3.81
31.5	0.5	12.7	0.33	0.76	8.382	19.304
36.9	1.0	25.4	0.66	1.51	16.764	38.354
42.3	2.0	50.8	1.32	3.02	33.528	76.708
45.4	3.0	76.2	1.98	4.54	50.292	115.316

13

3. STORM ANALYSIS

3.1 Storm Tracks

The storm center tracks for the periods during which snowfall measurements and radar reflectivity were recorded for the five 1978 snowstorms are indicated on a plotting chart, Figure 3. These tracks are representative of the normal New England northeast snowstorm.
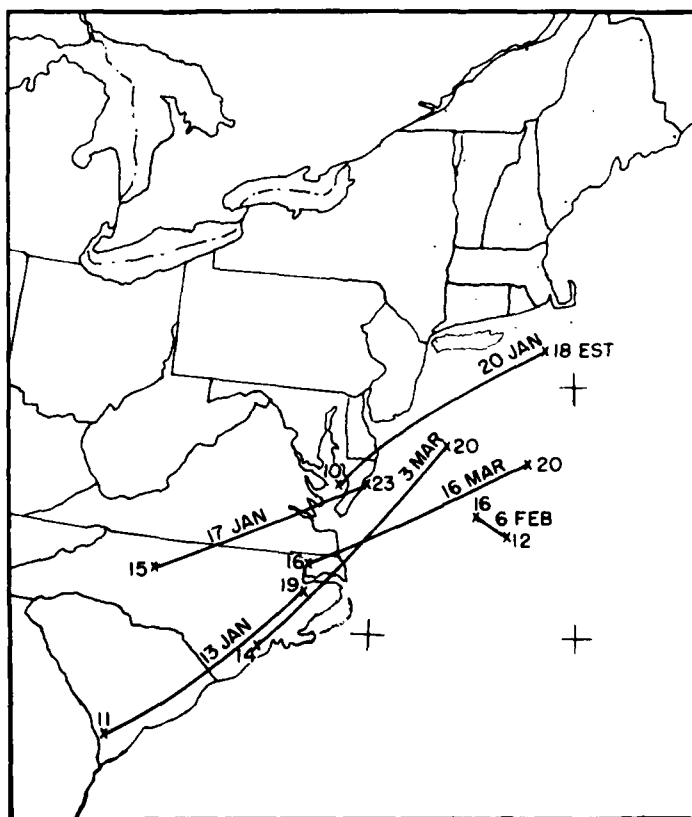

Figure 3. 1978 Snowstorm Center Tracks During Snow Accumulation—Radar Observation Periods

3.2 Storm of 20 January 1978

3.2.1 SYNOPTIC FEATURES

3.2.1.1 General Discussion

Excluding the record-breaking 6-7 February snowstorm, only briefly observed by radar at the start, the 20 January snowstorm was the heaviest of the 1978 series. It developed near the northern Florida Gulf coast and deepened over eastern North Carolina on 20 January. Light snow started in the AFGL radar area before daybreak on 20 January (Figure 3). The storm was centered along the Nova Scotia coast by 0700, 21 January.

A large east-west anticyclone was centered along the St. Lawrence River Valley at 0700, 20 January. At the 500 mb level, a sharp short-wave trough from a low centered over the northern Mississippi Valley extended south-southeastward to the Carolina coast at 0700, 20 January. This system progressed rapidly eastward, losing amplitude but accounting for the sustained speed of the snowstorm system.

3.2.1.2 Details of the Mesoscale Surface Analysis

Three mesoscale surface charts are shown in Figures 4, 5, and 6, giving at 0800, 1200, and 1600, 20 January: 1) the surface wind pattern; 2) the surface precipitation type and intensity reports; 3) the temperature, and 4) the CPS-9 reflectivity distribution. On the basis of hourly surface reports the heaviest snow falling at 0800, (Figure 4) extends from the radar site west-southwestward to the lower Hudson Valley. Only two stations at this hour, LaGuardia and JFK in the New York City area, are reporting ice pellets mixed with snow. The area of strongest reflectivity (42 dBZ +) is uniformly distributed in an east-west band centered on the radar site. The reflectivity diminishes rapidly to the north where light snow is just beginning at Concord and Lebanon, New Hampshire. The lessening of reflectivity toward the south is in part due to range attenuation as well as to the effect of the progressively higher elevation of the 0° radar beam into weaker snow echo and also to the vertical spreading of the 1° beamwidth.

Four hours later, at 1200 (Figure 5), the surface reports limit the heavy snow to an area extending about 45 km to the northwest, west, and southwest of the radar site but also spreading northeastward along the Maine coast. Areas of low radar reflectivity (36 dBZ or less) appear within 45 to 90 km to the northwest, west, and southwest. However, the significant reflectivity development is to the south, from Cape Cod to southwestern Connecticut. This latter area is the region where ice pellets are reported along with the snow. This feature, obviously, resulted in higher reflectivity at that range than was possible 4 h earlier when heavy snow was reported from the ground stations in that area. Again, as at 0800,
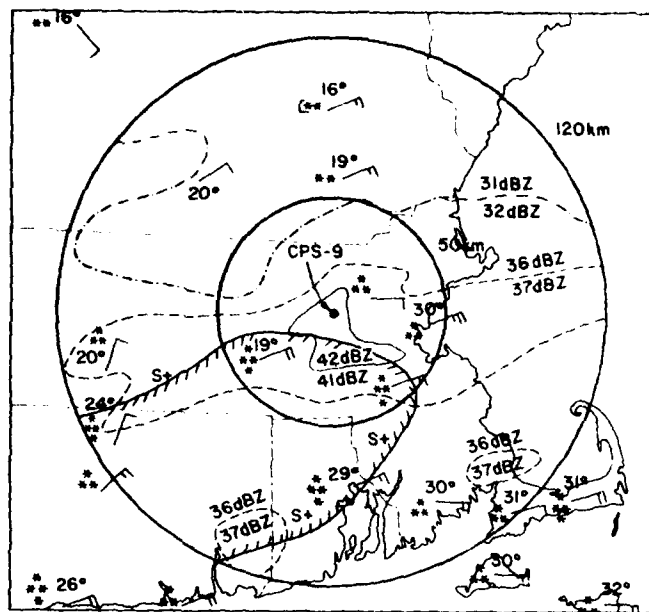
15

Figure 4. Mesoscale Surface Chart at 0800, 20 January
1978, Showing Surface Hourly Reports of Temperature,
Wind, Precipitation Intensity, and Radar Reflectivity
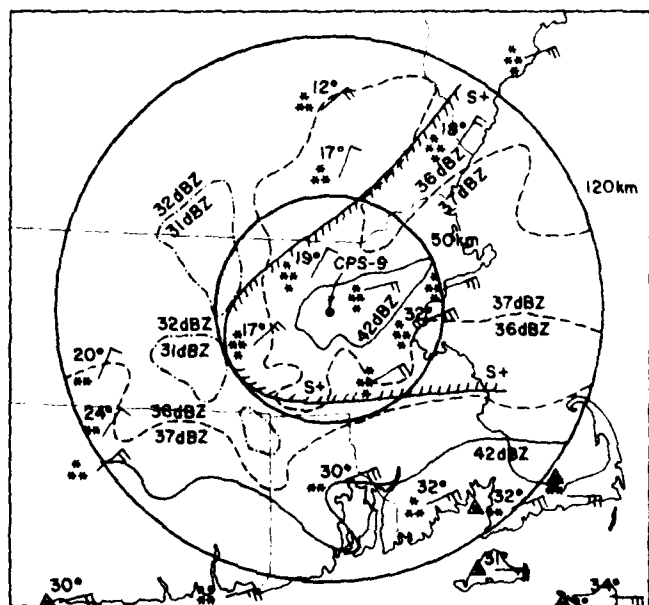Distribution

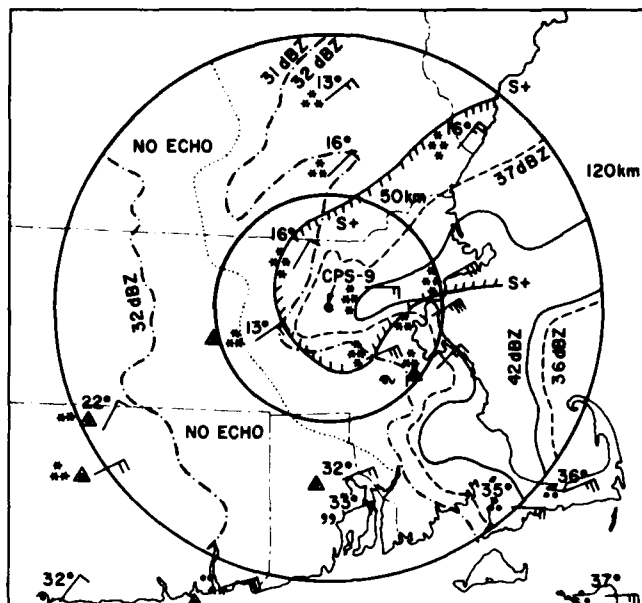Figure 5. Mesoscale Surface Chart at 1200, 20 January
1978

16

Figure 6. Mesoscale Surface Chart at 1600, 20 January
1978

reflectivity around the radar is high, 42 dBZ. But the long range reflectivity to
the south is very indicative of a melting layer aloft and the presence of a bright
band, as suggested by wet and partially melted snow, the regions from which sur-
face ice pellets are reported.

At 1600 (Figure 6) surface reports of heavy snow are now limited to Dedham,
Norwood, Ayer, Bedford, and Beverly, as well as Pease AFB in southeastern
New Hampshire. The band of high reflectivity, 40 dBZ or higher, along the south
coast at 1200, has now advanced northeastward, not only covering most of Cape
Cod, but has merged with the earlier area of strong reflectivity to the north. An
echo-free area extending north-northwest to south-southeast is found to the west
of the radar site but followed by another heavier, cellular reflectivity zone from
the Connecticut Valley westward. This latter is apparently related to the heavy
snow reported from the Albany surface report.

3.2.1.3 Storm Snowfall

The snowfall, as observed at the surface during a major snowstorm in New
England, generally tends to give the appearance of areal uniformity in contrast to
snow showers accompanying a cold front. However, the chart, Figure 7, showing
the distribution of snowfall measurements for the 20 January storm at the
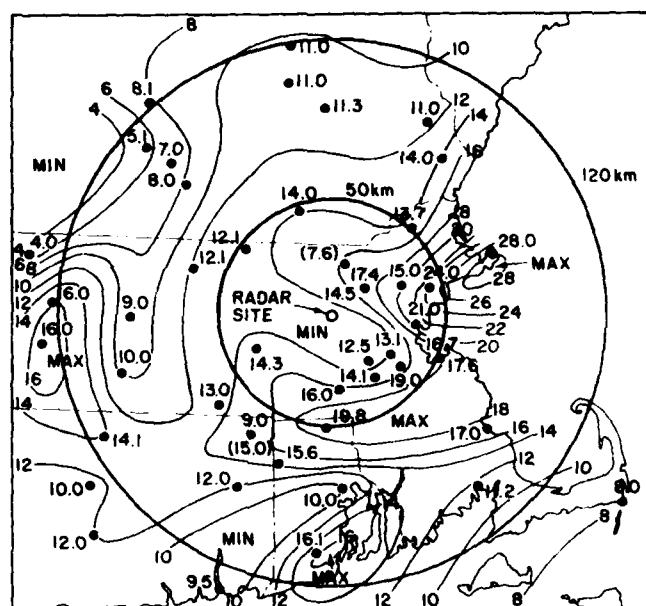
17

Figure 7. Total Storm Snowfall in Inches (in.), 20 January 1978

cooperative climatological stations, gives quite a different representation. The heaviest snowfall area in this storm extended northeastward from a 21-in. (533.4 mm) total at Logan Airport, to 24 in. (609.6 mm) at Peabody, and the storm maximum of 28 in. (711.2 mm) at Rockport, Massachusetts. Another maximum zone occurred south of Boston, 19.8 in. (502.9 mm) at Woonsocket, Rhode Island. Lighter amounts fell immediately to the southeast of the radar site, including 12.5 in. (317.5 mm) at Natick, 13.1 in. (332.7 mm) at Dedham, and to the northeast, 14.5 in. (368.3 mm) at Lexington, 15 in. (381.0 mm) at Reading, and 17.4 in. (442.0 mm) at Bedford appears a bit too high.

No rain was reported at any of the snow measuring points. However, ice pellets were reported at Hingham, Dedham, and Natick from 1500 to 1630 or 1700, and also reported briefly at Lexington. Other stations reporting ice pellets were Worcester and Logan Airport. The snowfall distribution for this storm serves as an example of the difficulty involved in forecasting the geographical variation of the snowfall in a New England snowstorm, solely on the basis of synoptic charts and hourly teletype reports.

18

3.2.1.4 Snowfall-Reflectivity Correlation

The storm of 20 January was the second heaviest snowstorm of the winter.
An important feature is that the data points on the snowfall rate — reflectivity
correlation diagram, Figure 8, are concentrated at the high snowfall rates and
high reflectivity values. Mean snowfall rate for 20 January datum is 1.06 in. h^{-1}
(26.92 mm h^{-1}) and mean reflectivity is 34.8 dBZ. Due to the concentration of
data, the correlation of snowfall rate versus reflectivity is thus more affected by
the variance of the values and the resulting correlation coefficient for the 50 pairs
of data points is only r = 0.613. The regression equation for the 20 January data
is

$$S = 0.0989 \ Z^{0.3703} \ .$$

Its locus, shown on Figure 8, is not in good agreement with that for the entire
1978 data, also indicated on the January correlation diagram. This emphasizes
the importance of using a sufficiently large collection of data yielding a good dis-
tribution of snowfall rates and reflectivities in order to offset the deleterious ef-
fect of the scattering of snowfall rate measurements and radar reflectivity values
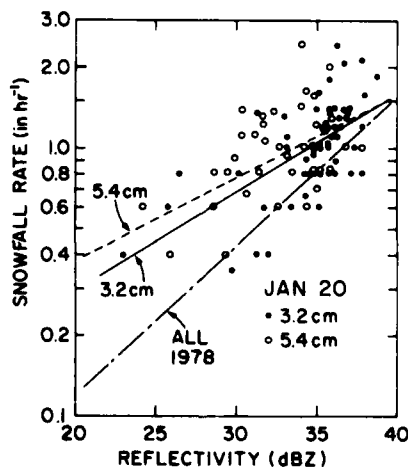about the regression line.

Figure 8. Correlation of 20 Jan-
uary Snowfall Rates and Radar Re-
flectivities for the 3.2 cm and
5.4 cm Radars. Comparison with
the correlation line for the entire
1978 snowfall-radar data

19

Both the 3.2 cm and the 5.4 cm radar data, however, compare very favorably. As indicated in the statistical analysis of the 3.2 cm data, a 15-min lag was also used for the 5.4 cm data. Because of a shorter operating period, the 5.4 cm radar, scanning at 0.7° elevation angle, covered only 35 observation points, also plotted in Figure 8. Correlation coefficient for this distribution was $r = 0.552$. By comparison, the 3.2 cm radar data for this same time period was slightly higher, $r = 0.597$. From these results, the digitized reflectivity from the 5.4 cm radar appears to be another accurate means of obtaining useful snowfall rate data, but not superior to the 3.2 cm radar data.

3.3 Summaries of Other 1978 Snowstorms

3.3.1 13 JANUARY STORM

During this storm, cold air with subfreezing temperatures was maintained in the lower levels in the snow observing areas. However, warmer air overran the lower cold air and the result was a prolonged period of ice pellets amounting to about 3 in. (76 mm) at Natick and Dedham in addition to the 3.1 to 3.4 in. (78.7 to 86.4 mm) of snow falling during the snowfall project operating period. The narrow range of snowfall rate and reflectivity resulted in a correlation coefficient of $r = 0.67$. Snowfall rates were from 0.1 in. h^{-1} (2.5 mm h^{-1}) to 0.7 in. h^{-1} (17 mm h^{-1}) while reflectivity ranged from 21.7 to 32.0 dBZ.

3.3.2 17 JANUARY STORM

This storm produced the least snowfall for the operating period of any of the 1978 snowstorms in this project. Total snowfall amounts ranged from 1 to 1.5 in. (25.4 to 38.1 mm). Another factor was the rapid advection of warm air aloft producing a change to rain. However, in spite of the light snowfall, the correlation coefficient between snowfall rate and radar reflectivity for this storm was $r = 0.87$. Snowfall rates changed from 0.04 in. h^{-1} (1.0 mm h^{-1}) at Dedham, with a reflectivity value of 10.9 dBZ, to 0.7 in. h^{-1} (17.8 mm h^{-1}) at Natick with the reflectivity up to 34.4 dBZ.

3.3.3 3 MARCH STORM

While this storm resembled the 20 January storm, it advanced more rapidly and the snowfall during the measuring period ranged from 5.8 in. (147.3 mm) at Dedham to 3.2 in. (81.3 mm) at Reading. A widespread range of snowfall rates from 0.1 in. h^{-1} (2.5 mm h^{-1}) to 1.4 in. h^{-1} (35.6 mm h^{-1}) accompanied by reflectivity values of 23.2 to 38.9 dBZ gave the highest individual storm correlation of $r = 0.919$. The air remained cold, surface temperatures in the 20s. The six observations from two measuring stations at the start of the 6 February storm were considered a part of the 3 March storm.

3.3.4 16 MARCH STORM

As seen on Figure 3, the storm center of this last storm of the 1978 series remained further south than any of the previous centers. Although surface temperatures were slightly above freezing at the start of the snow in the observing area and the initial snow was wet, no ice pellets nor rain were observed, and temperatures dropped to subfreezing levels. Snowfall ranged from 3.5 to 2.7 in. (88.9 to 68.8 mm) at the measuring sites, while the snowfall rate ranged from 0.2 to 1.5 in. h^{-1} (5.1 to 38.1 mm h^{-1}), and the corresponding reflectivity 25 to 38 dBZ. Discrepancies between snowfall rate and reflectivity were noted during the early portion of the storm when the snow was wet. This may be, in part, responsible for the correlation coefficient $r = 0.79$ for this storm.

4. TOTAL STORM SNOWFALL AS DETERMINED BY RADAR REFLECTIVITY

4.1 Introduction

In all cases where the determination of snowfall from radar reflectivity measurements is performed, either after the storm has ended, or seasonally, a technique is available to successfully correlate measured total storm snowfall, (S_M), and snowfall values from radar reflectivity, (S_R). While radar equipment should continue to be electronically calibrated and the transmitter and receiver should be maintained to perform at rated values, discrepancies in the reflectivity measurements nevertheless still do occur. Irregularities in the radar measurement of snow due to variations in the physical characteristics of snow and particle fall speed do account for some of the variances. Such difficulties may be minimized by the use of a reference, or calibrating, snow measurement station to determine the optimum value of "a" in $Z = aS^b$, where "b" value may be kept constant. In statistical studies of storm totals, Carlson and Marshall (1972)[1] and Jatila (1973)[2] kept "b" equal to 2. Wilson (1975)[3] used b = 2.21 but stated that choice of any ... "value of "b" between approximately 1.9 and 2.4 would have little effect on the accuracy of the radar estimates."[3] Harrold, et al (1974)[10] and Collier and Larke (1978),[4] both probably using b = 1.6, have also successfully used this same technique to improve the correlation coefficient. In brief, this technique is an operational calibration of the radar by adjusting the regression line for the best fit between storm snowfall (S_M) and radar determined snowfall (S_R) for selected test station(s). Use of such a technique leads to an optimum correlation for the other measuring sites.

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10. Harrold, T.W., English, E.J., and Nicholass, C.A. (1974) The accuracy of radar-derived rainfall measurements in hilly terrain, Quart. J.R. Met. Soc. 100:331-350.

4.2 Correlation of 1978 Storm Total Measured Snowfall versus Radar Determined Snowfall

Two snowfall measuring sites, Dedham and Natick, were selected to be used for reference or calibrating data. For this purpose the equation, $Z = aS_M^2$ was first utilized to determine "a" (a_{ref}) for both Dedham and Natick. The snowfall, S_R, from radar reflectivity, Z, at other snow measuring stations was then determined by

$$\bar{S}_R = \sqrt{\frac{\bar{Z}}{a_{ref}}} \quad ,$$

where $\bar{S}$ is the average snowfall rate, and $\bar{Z}$ is the average reflectivity for the storm. The final step was to correlate the average values of the total storm snowfall rates, as measured at each snow measuring site, with the average reflectivity over each site. The end products are two sets of values, shown in the two correlation diagrams, Figures 9 and 10. The first one of these, Figure 9, used Dedham as a reference station. The correlation coefficient is $r = 0.956$, and the regression line is $\bar{S}_M = \bar{S}_R^{0.96} + 1.246$. Figure 10 is the second correlation diagram, using Natick as a reference station. The correlation coefficient is $r = 0.963$ and the regression line is $\bar{S}_M = \bar{S}_R^{0.94} + 0.993$. Both diagrams represent excellent correlations, very similar to the results of Jatila (1973)[2] in correlating Finland snowfall and radar reflectivity.

4.3 Conclusion

The conclusion is simple. For optimum accuracy in determining snowfall for storm totals and for hydrological or climatological purposes after the storm, obtain the best correlation between actual snowfall, (S_M), and radar determined snowfall, (S_R), by the use of one or two reliable measuring stations to adjust or calibrate for the regression that best fits the data.

5. GENERAL CONCLUSION BASED ON CONSIDERATION OF ALL 1978 STORMS

The main target of this project was to evaluate the probability that the correlation of radar reflectivity and snowfall rate measurements, performed during the significant snowstorms of a winter season, would yield an operationally useful technique to determine snowfall rates solely from radar reflectivity measurements.

Individually, for each of the five snowstorms which, when taken together, form the body of the data in this project, a correlation between the snowfall rate and the radar reflectivity (not shown) was prepared as part of the initial analysis. When
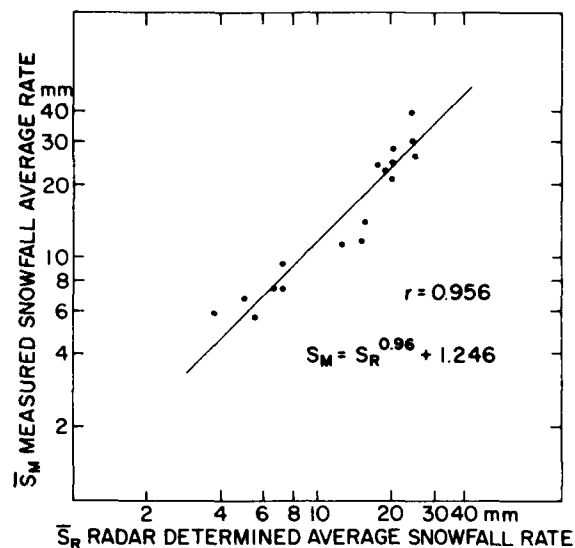
Figure 9. Correlation of Total Storm Snowfall
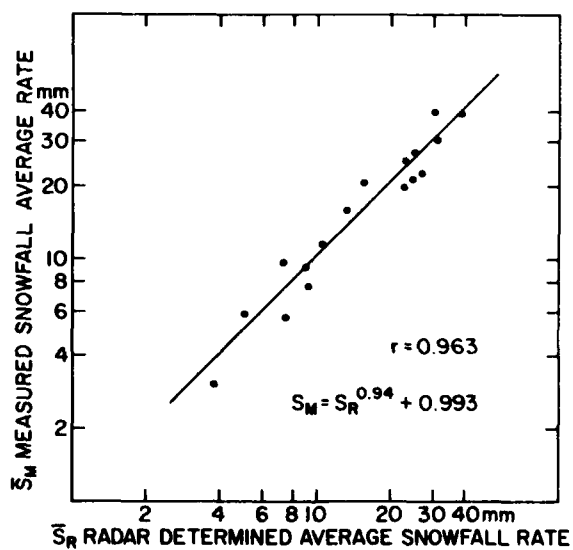Rates and Radar Reflectivity Using Dedham as
Reference Station

Figure 10. Correlation of Total Storm Snowfall
Rates and Radar Reflectivity Using Natick as
Reference Station

23

compared with the regression line for all of the combined 1978 storms, as shown in Figure 2, the individual storms compared very favorably. There was one exception, however. The regression line for the 20 January snowstorm, as shown in Figure 8, was radically different from the 1978 regression line for reasons discussed in the 20 January analysis. In spite of this apparent misfit, a composite (not shown) of all three January storms and the regression for the entire 1978 data are almost duplicates. There is some validity to the argument that the correlation between radar reflectivity and snowfall rate will vary from storm to storm due to differences in snow crystal types and fall speed of snow between storms and even during the same storm, as explained by Ohtake and Henmi (1970).[7] However, from the overall statistics of the combined 1978 winter data, the utility of a single overall regression line seems justified in the application of this research to facilitate determining snowfall rates from radar reflectivity during the storm.

The most significant result of this study is a demonstration of a reliable, operationally useful technique for estimating snowfall rate and snowfall amounts within a 50 km range of a 3.2 or 5.4 cm radar during a snowstorm on the basis of observed radar reflectivity.

A useful program developed to perform this service and to supply operational data values to users would, first, quantize the reflectivity over critical points such as airports, major highways, and urban congested areas and then, by means of the regression line given in this report, convert the measured reflectivity to a snowfall rate estimate at half-hour or hour intervals. The end product would be periodic charts of estimated snowfall rates or snow accumulation at these locations.

For climatological and other purposes, not requiring contemporary snowfall rate and radar observations, the correlation is greatly improved by calibrating the averaged measured storm snowfall and the snowfall rate computed from radar reflectivity. This process performs two types of beneficial alterations. It readjusts the regression line by making it pass through the point representing the average measured snowfall rate and the snowfall rate determined from reflectivity and averaging the snowfall rate and reflectivity for the entire storm eliminates much of the variance introduced by hourly and half-hourly measurements. Compared to the correlation coefficient of snowfall rate determined by reflectivity during a storm, r = 0.88, the referenced storm total data increased the correlation coefficient to a very significant r = 0.96.

References

1. Carlson, P. E., and Marshall, J. S. (1972) Measurements of snowfall by radar, J. Appl. Meteor. 11:494-500.

2. Jatila, E. (1973) Experimental study of the measurement of snowfall by radar, Univ. of Helsinki, Dept. of Met. Paper No. 122, Geophysica 12(No. 2):1-10.

3. Wilson, J. W. (1975) Measurement of Snowfall by Radar During the IFYGL, Preprints, 16th Radar Meteor. Conf., Amer. Meteor. Soc., Boston, Massachusetts, 508-513.

4. Collier, C. G., and Larke, P. R. (1978) A case study of the measurement of snowfall by radar: An assessment of accuracy, Quart. J. R. Met. Soc. 104:615-621.

5. Boucher, R. J. (1978) Correlation of Radar Reflectivity and Snowfall Rate During Moderate to Heavy Snow, Preprints, 18th Conf. on Radar Meteorology, Amer. Meteor. Soc., Boston, Massachusetts, 328-331. AFGL-TR-78-0079, AD A053 186.

6. Boucher, R. J. (1980) Snowfall Rate Determined from Radar Reflectivity, Preprints, 19th Conf. on Radar Meteorology, Amer. Meteor. Soc., Boston, Massachusetts, 438-439. AFGL-TR-80-0131, AD A084 297.

7. Ohtake, T., and Henmi, T. (1970) Radar Reflectivity of Aggregated Snowflakes, Preprints, 14th Radar Meteor. Conf., Amer. Met. Soc., Boston, Massachusetts, 209-210.

8. Nakaya, U. (1954) Snow Crystals Natural and Artificial, Harvard Univ. Press, Cambridge, Massachusetts.

9. Petrocchi, P. J. (1976) Operational Capability of a Weather Radar Time Lapse Color Display System, Preprints, 17th Radar Meteor. Conf., Amer. Meteor. Soc., Boston, Massachusetts, 562-565. AFGL-TR-76-0257, AD A032 005.

10. Harrold, T. W., English, E. J., and Nicholass, C. A. (1974) The accuracy of radar-derived rainfall measurements in hilly terrain, Quart. J. R. Met. Soc. 100:331-350.

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82